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Performance Analysis for Partial Feedback Downlink MIMO with Unitary Codebook Beamforming for LTE

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Abstract: Until recently, mobile communication tasks have been grouped into different layers in a hierarchical layer approach. In this conventional approach, layer-specific protocols are developed and optimised independently. As new wireless applications emerge, requiring high data rates and flexibility for supporting applications with significantly varying QoS requirements, it has become imperative that a higher level of communication between adjacent layers needs to be established. A unitary codebook based beamforming approach has been proposed for LTE that incorporates an improved cross-layer interface in order to improve service to users according to specified QoS criteria. This paper examines this beamforming approach under partial feedback conditions for different MIMO configurations. It is shown that non-obvious precoding matrix selection strategies and scheduling policies for the DL, can achieve superior performance for LTE system, whilst meeting the QoS requirements of urgent users.

I. INTRODUCTION

Emerging wireless communications systems that include a variety of different applications (e.g. real time video, voice, data) have changed the scope and design principles of wireless technologies. The need to provide high data rates for users within a congested channel environment has resulted in the emergence of Multiple Input Multiple Output (MIMO) antenna technologies and Orthogonal Frequency Division Multiplexing (OFDM). OFDM splits a high data rate stream into several lower rate orthogonal parallel streams. This approach is an attractive solution towards designing systems that are expected to operate in Non Line-of-Sight (NLOS) channels due to high tolerance to delay spread effects achieved by the a longer symbol duration and the use of a Cyclic Prefix (CP). The additional degree of freedom enabled by the use of multiple antennas at the transmitter and the receiver enables multiple users to be simultaneously scheduled on the same subchannel, or the assignment of multiple streams to the same user.

The advent of new wireless applications, has highlighted the need for a better cross-layer cooperation that can support traffic with flexible Quality of Service (QoS) requirements, such as maximum packet delay, constraints of successful packet transmission. Recently, a Multiuser, Multiple Input Multiple Output (MIMO) scheduling and precoding method has been proposed for the Long Term Evolution (LTE) of 3G systems [1], that incorporates an improved interface between the Physical (PHY) and the Data Link Control (DLC) layers in order to provide increased support for on demand QoS [2]. In [3], a precoding method for a MIMO-OFDMA scheme has been proposed in accordance to the LTE standard [1]. This precoding method relies on the use of a known codebook of unitary matrices, which is determined offline, generated

according to a Fourier basis that provides uniform coverage across a sector.

The benefits from the symbiotic effect of a cross-layer design have been studied in [2]. This paper considers different codebook sizes of unitary precoding matrices and proposes beam selection and scheduling approaches for different MIMO configurations for the LTE standard. Performance analysis considers both Spatial Multiplexing of multiple data streams to the same user (SDM), as well as Spatial Multiplexing of multiple data streams to different users (SDMA).

II. SYSTEM PARAMETERS AND CHANNEL MODELS

In this study an OFDMA system with 10MHz total bandwidth is used. A total number of 1024 subcarriers is assumed. The modulation and coding scheme is adaptively determined, based on received Signal to Interference plus Noise Ratio (SINR) information from the mobile terminal.

Table 1 summarizes key system and simulation parameters used in this paper.

Table 1: Parameters of the proposed OFDMA system

PARAMETERS	VALUE
System	OFDMA
Downlink channel bandwidth	10 MHz
No. of transmit antennas	2
No. of receive antennas per MS	2
Precoding codebook size	1/2/4/8
FFT size	1024

III. UNITARY BEAMFORMING WITH CROSS-LAYER COOPERATION

Opportunistic scheduling examined in a number of papers, e.g. [4, 5] relies on the principle that a system benefits most from the fading conditions of a wireless channel by allocating resources to the user that can best utilise this channel for every scheduling instant. Random Beamforming is an extension of opportunistic scheduling to a MIMO system that utilizes Singular Value Decomposition (SVD) [6, 7]. The Random Beamforming principle has been extended to a multicarrier, OFDMA scheme in [8, 9], where significant performance benefits have been observed, due to the increased multiuser diversity arising from OFDMA. In principle, this Random Beamforming scheme relies on feedback of SINR values from MSs, regarding a unitary matrix V_r . Different V_r are generated for different clusters of subcarriers.

For a 2x2 Random Beamforming system, the MIMO channel consists of two subspaces that can be considered as 2 data streams transmitting through 2 parallel sub-channels. The

MIMO channel matrix \mathbf{H}_k for the k -th MS is denoted as follows:

$$\mathbf{H}_k = \begin{bmatrix} h_{1,1} & \dots & h_{1,M} \\ \vdots & \ddots & \vdots \\ h_{N,1} & \dots & h_{N,M} \end{bmatrix} \quad (1)$$

Where $h_{i,j}$ denotes the channel impulse response coupling the j -th antenna at the BS and the i -th antenna at the MS.

The unitary matrix V_r is generated from a randomly generated channel matrix H_r and is applied to the subcarriers of the OFDM signal on a cluster basis. The received signal after the FFT and guard interval removal becomes:

$$\begin{aligned} Y_k^s &= H_k^s V_r^s X_t^s + N_k^s \\ &= U_k^s D_k^s (V_k^s)^H V_r^s X_t^s + N_k^s \end{aligned} \quad (2)$$

H_k^s being a matrix containing the frequency responses of the channels between N_t transmit and N_r receive antennas for a subcarrier or a group of adjacent subcarriers with highly correlated channel responses, which will be called a cluster. D_k^s is the diagonal matrix including all singular values of H_k^s , U_k^s and D_k^s are the unitary matrices obtained by applying SVD to H_k^s . X_t^s denotes an $N_t \times 1$ matrix containing the transmit signals at subcarrier s at the BS and N represents the additive complex Gaussian noise. The Minimum Mean Squared Error (MMSE) is the most commonly used detection method for transmitted data. Using an MMSE filter the SINR of the k -th user for its q -th stream is given by:

$$\text{SINR}_k^q = \frac{|D_k^s|_{qq}^2 |(V_k^H V_r)_{qq}|^2 E_s}{|D_k^s|_{qq}^2 |(V_k^H V_r)_{qj,q+j}|^2 E_s + N} \quad (3)$$

In codebook based precoding, where unitary matrices are determined offline, cross-layer cooperation allows MSs to identify suitable beams that will provide preferential channel conditions to users according to specified QoS criteria. The technique described in [3] suggests that each mobile station can select a preferred beam from a predefined set of antenna beams that have been designed offline, which altogether ensure good sector coverage [10]. The proposed pre-coder design relies on the Fourier basis for ensuring uniform sector coverage. The codebook \mathbf{E} , consists of the unitary matrix set, i.e. $\mathbf{E} = \{\mathbf{E}^{(0)} \dots \mathbf{E}^{(G-1)}\}$, where $\mathbf{E}^{(g)} = [e_0^{(g)} \dots e_{M-1}^{(g)}]$ is the g -th precoding matrix, and $e_m^{(g)}$ is the m -th precoding vector in the set. According to the Fourier basis,

$$\begin{aligned} e_m^{(g)} &= \frac{1}{\sqrt{M}} [w_{0m}^{(g)} \dots w_{(M-1)m}^{(g)}]^T \\ w_{nm}^{(g)} &= \exp\left\{j \frac{2\pi}{M} \left(m + \frac{g}{G}\right)\right\} \end{aligned} \quad (4)$$

Knowledge about suitable beams can be exploited in the beamforming step in order to maximise the QoS objective, of identifying strong clusters and serving them with preferential beams. By taking into consideration different QoS metrics, such as packet delay, packet timeout ratio etc., or even factors that concern traffic management, e.g. premium service or

traffic capping, a set of eligible users can be identified, for which preferential beams can be selected.

IV. INTRODUCTION TO BEAM SELECTION WITH PARTIAL FEEDBACK

Efficient opportunistic scheduling relies on SINR information from MSs to be provided at least at the rate which the channel is changing. The combined use of opportunistic scheduling and OFDMA increases the required uplink feedback information that can significantly mitigate diversity gains. In [11], an opportunistic scheduling scheme has been examined for a MISO system, where additional diversity gains were extracted by the use of multiple weighting vectors. However the use of multiple vectors, or in a MIMO scenario, multiple matrices, results in a Q -fold increase in the uplink overhead, where Q is the number of weighting vectors. Therefore the combined use of OFDMA and multiple precoding design results in an excessive feedback overhead. For this reason various approaches for uplink feedback reduction in OFDMA and multiple precoding selection have been developed [12, 13]. This section outlines the basic procedure followed for the unitary beamforming, illustrated in Figure 1, based on a pre-defined codebook with partial feedback design, as proposed in [3].

- At the preamble phase (DL), pilot symbols are transmitted to MSs for channel estimation purposes. The SINR is calculated on each physical resource block (PRB) by each MS.
- At the feed back phase (UL) each MS feeds back the Channel Quality Indicator (CQI) for all the subsets of its "preferred precoding matrix" according to estimated SINR from all pre-coding matrices. A preferred matrix indicator is also transmitted. The index of the matrix position within the codebook is most commonly used.
- According to the gathered information at the receiver, users declaring the same preferred pre-coding matrix are grouped together.
- The group with the highest priority (based on a selected scheduling algorithm) and the corresponding unitary matrix is determined for the current PRB.
- For a Single-User MIMO (SU-MIMO) scheme realising SDM, the user with the highest priority is identified. For a Multi-User MIMO (MU-MIMO) scheme realising SDMA, streams from multiple users with the highest priority are selected. (It is assumed here that users controlling beam selection have the same priority, as determined from their QoS conditions. Hence the scope in this case is to maximise overall system capacity.)
- Appropriate Adaptive Modulation and Coding (AMC) is applied to the selected streams.
- The selected precoding matrix is applied to the selected user group.

What is evident from the above procedure is that a policy for selecting preferred precoding matrices at the receiver, as well as determining group priorities at the transmitter, remains unspecified, allowing different vendors to adopt different strategies. By adopting an opportunistic scheduling approach, where PRBs are assigned to the MSs that can best utilise these resources, multiuser diversity gains can be extracted.

Subsequent sections of this paper consider different strategies for beam and group priority selection for both SU-

MIMO and MU-MIMO, and through analytical simulations optimum methods for partial feedback are proposed.

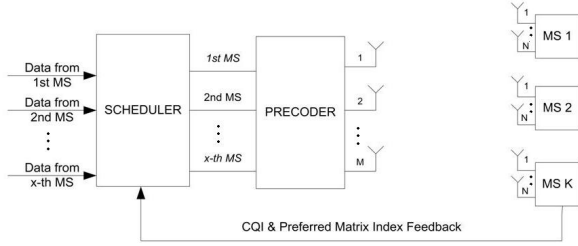


Figure 1: Unitary Codebook Beamforming Configuration

V. BEAM SELECTION AND GROUP PRIORITIES FOR SU-MIMO WITH PARTIAL FEEDBACK

In SU-MIMO systems, both streams are assigned to the same mobile station (SDM). The primary objective therefore is to select the user with the best SINR performance across both streams and assign to it its best beam.

As a first step, we consider a simple rate maximization criterion where each MS selects the preferred matrix according to the sum SINR across both streams. The BS selects the preferred precoding matrix according to the index of the selected precoding matrix of the MS with the highest sum SINR. As shown in Figure 2, theory suggests that by increasing the codebook size from $L=1$ to 8, higher multiuser diversity gains arise, that consequently increase the average system capacity of the SU-MIMO system.

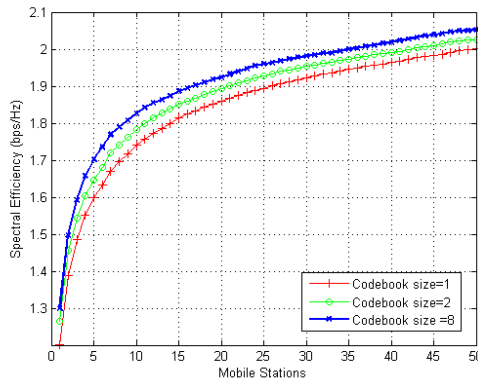


Figure 2: Theoretical capacity for SU-MIMO with unitary codebook beamforming

Figure 3 shows the Bit Error Rate (BER) performance of this system employing QPSK modulation and 3/4 coding rate for a total number of mobile stations, $K=12$. Contradictory to theory, it is observed that performance actually degrades with the introduction of multiple precoding matrices in the system, despite the obvious increase in multiuser diversity gains. The answer to this paradox lies in the nature of the precoding matrices. With a larger codebook size, the probability of identifying a matrix that results in a higher sum of subspace SINRs increases. Examining, however the individual subspace SINRs, it is observed that the overall increase in channel gain is attributed only to one subspace, while the strength of the weaker subspace degrades even further. Despite the overall increase in diversity, the performance benefits arising from the strong subspace are outweighed by

the resulting degradation of the weak subspace. This is consistent with observations made in [14].

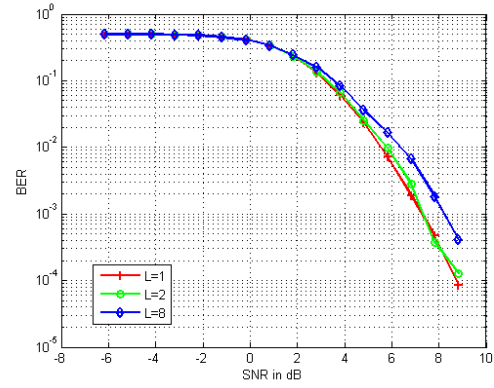


Figure 3: BER performance of SU-MIMO for subspace sum SINR maximisation metric

Therefore, a second approach, where improving the gain from the weak subspace seems to be a more suitable approach for improving the overall performance of a partial feedback SU-MIMO. In this scenario the preferred matrix is selected according to the channel strength of the weakest subspace, irrespective of the strength of the stronger subspace. Two scheduling approaches at the transmitter are considered. The BS can either select the beam according to the MS with the highest sum SINR, or the strongest weak subspace approach in the scheduling process can be followed as well.

Figure 4 shows the resulting BER performance of these approaches for a codebook size $L=8$. It can be seen that by having the "preferred beam" selection being dependent on the weak subspace channel strength, rather than the aggregate subspaces strength, a coding gain does in fact arise from the use of multiple precoding vectors, despite the fact that the conventional rate maximisation scheduling policy is not followed. Employing the best weak subspace selection in the scheduling stage results in minor performance degradation with respect to the maximum rate scheduling process. This is due to some loss in diversity. Ensuring that the preferred beam selection process at MSs maximises the weak subspace seems to be an adequate step for performance optimisation. Figure 5 presents BER curves for different codebook sizes for the best weak subspace policy, showing added benefits with an increased codebook size.

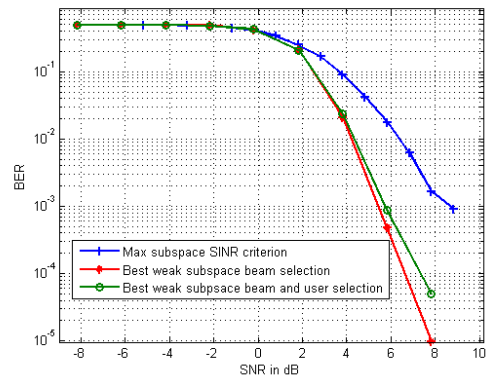


Figure 4: SU-MIMO BER Performance for different beam and user selection policies

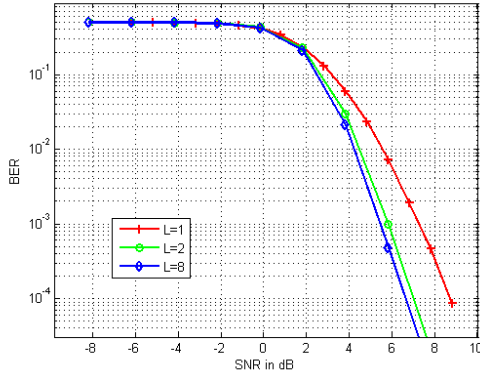


Figure 5: BER performance of SU-MIMO with weak subspace maximization for different codebook sizes

The nature of the precoding matrices is such that a rate maximisation policy that does not take into account individual subspace conditions fails to provide any performance benefits with an increased codebook size.

VI. BEAM SELECTION AND GROUP PRIORITIES FOR MU-MIMO WITH PARTIAL FEEDBACK

SU-MIMO assigns all streams of a PRB to the same MS. However a more efficient spectrum utilisation and better system performance can be achieved by exploitation of diversity in the spatial domain. As indicated in Figure 6, spectral efficiency is expected to increase if multiple users are allowed to share the same resource block by being allocated different streams of the MIMO channel in an opportunistic manner. Full feedback is assumed, where CQI from all precoding matrices is fed back by each MS to the transmitter.

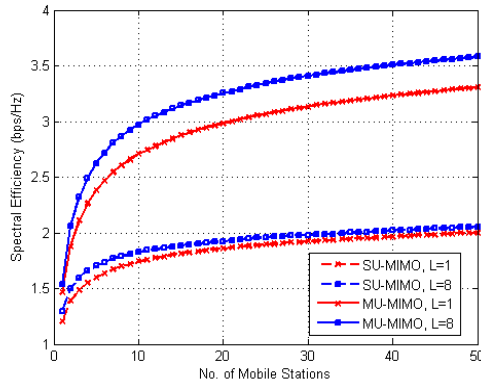


Figure 6: Theoretical capacity for SU-MIMO and MU-MIMO with unitary codebook beamforming

Optimising performance for MU-MIMO with partial feedback information is a more complex task than for SU-MIMO, since two different MSs can be assigned on the same resource block. In a full feedback MU-MIMO scheme, where MSs feed back CQI values regarding all matrices of the codebook, centralised decisions for optimum beam and group selection that can maximise gains on both streams can be efficiently performed by the BS. With partial feedback however, this centralised optimisation process cannot take place since the BS receives information that maximises individual MSs performance; this information does not ensure

optimum system performance however. The optimisation problem becomes increasingly complex as the codebook size increases, since the probability of identifying a user group that maximizes SINR on both layers reduces.

Two selection criteria for preferred matrix selection have been identified for partial feedback MU-MIMO.

- Best Subspace SINR criterion.
- Sum Subspace SINR criterion.

Since MU-MIMO results in increased probability that a selected MS will be allocated resources only on its strongest stream, selecting a preferred matrix according to the SINR of the strongest subspace would result in higher diversity gains. The Best Subspace SINR criterion performs this selection process. The SINR of the weak subspace is ignored in the preferred beam selection process, since it is rather unlikely that this subspace will actually be allocated to the MS, provided there is a sufficient number of alternative MSs.

The number of MSs in the scheduling process is determined by QoS criteria, and might therefore be limited to a small number of urgent users. Having a large codebook size under these conditions might result in a situation where no two MSs are identified for the selected matrix that can maximise different subspaces of the common PRB. When these conditions occur, the probability of selecting a weak subspace increases, consequently degrading performance. The Best Layer SINR criterion approaches optimal performance whenever a precoding matrix that increases subspace SINR on both streams is identified. The likelihood of this event depends on the size of the preferred user group. For a fixed number of users, this parameter depends on the codebook size, since more users will be identified for the same preferred matrix if the choice of matrices is limited. Consequently, it can be deduced that for a MU-MIMO system, an appropriate codebook size should be adaptively determined as a function of the number of available MSs, in order to extract the full benefits of multiuser diversity by ensuring that both subspaces are maximised.

The Sum Subspace SINR criterion has been designed in order to reduce the probability that CQI for weak subspaces is fed back to the BS by selecting the matrix that returns an overall good performance across both subspaces, despite the fact that only one of these layers is most likely to be scheduled. This approach can result in a reduced diversity, since it excludes exceptionally strong subspaces from being selected, due to the averaging effect of the aggregate SINR criterion. On the other hand, this process ensures that relatively strong subspaces are identified even for a large codebook, where the number of users in the preferred group may be limited. It is therefore suggested that this approach should be adopted when the number of MSs participating in the scheduling process is small.

BER performance of the partial MU-MIMO schemes with a codebook size $L=8$ are presented in Figure 7. Simulations for different numbers of active MSs have been considered, $K=12, 50$. As expected, for a small number of MSs, $K=12$, the partial feedback strategy fails to extract diversity gains from a large codebook, due to a resulting small selected user group, that fails to optimise performance on both layers, due to reduced multiuser diversity. The Sum Subspace criterion is only marginally better than the Best Subspace SINR criterion. An increased number of active MSs increases the multiuser diversity of the system that translates into a BER improvement for a full feedback scenario. For partial

feedback, only the Best Subspace Criterion is considered as this approach becomes more efficient for a large number of users, due to increased likelihood of optimising both subspaces, by having more users available for the selected precoding matrix.

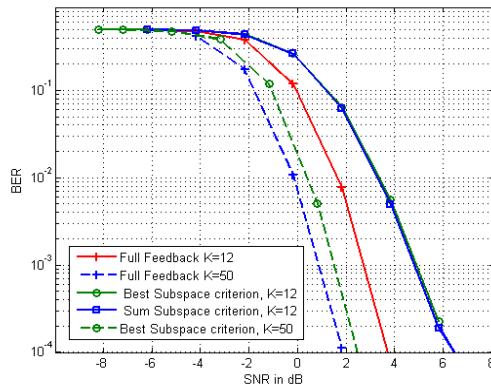


Figure 7: Partial Feedback MU-MIMO Beam Selection and Scheduling policies

VII. CONCLUSIONS

In this paper, the concept of beam selection and user scheduling of unitary codebook based beamforming with partial feedback for SU-MIMO and MU-MIMO, as proposed for LTE, has been addressed and analysed in detail. Partial feedback methods are required for opportunistic scheduling, OFDMA schemes, due to the large associated feedback overhead arising in a joint time/frequency resource allocation policy. SU-MIMO systems have shown to be more susceptible to performance degradations arising from a reduction of SINR on the weakest subspace. A new beam selection policy that ensures that both subspaces of the serviced users have relatively good channel conditions has shown to provide better performance. Optimizing MU-MIMO with partial feedback is a more complicated task, since a degree of communication between MSs for determination of the best beam is required, but is not feasible in practice, in a centralised Base Station configuration. Two different techniques have been investigated for MU-MIMO that can be applied under different traffic conditions. Results show that partial feedback techniques are harder to be employed successfully for MU-MIMO, especially for a large codebook size, as this gives rise to poor multiuser diversity exploitation. It is therefore suggested that the codebook size should be adaptively determined with regards to the number of MSs in order to fully exploit the diversity gains from multiple unitary matrices.

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